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Collective spontaneous emission of femtosecond pulses in quantum-well semiconductor lasers

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Abstract. A new type of accessible sources of ultrashort optical pulses based on the phenomenon of collective coherent recombination (superradiance) of electrons and holes in semiconductor heterostructures is proposed. The novel regime of an ultrafast operation of quantum-well semiconductor lasers is analyzed, in which a quasiperiodic sequence of superradiant pulses of duration up to 30 fs and peak intensity exceeding 100 MW/cm^2 is emitted under a continuous pumping from a low-Q cavity of length $\sim 30-100\,\mu$m.

1 Introduction

Superradiance (SR) in an ensemble of excited two-level atoms was predicted by Dicke in 1954 and confirmed experimentally in the seventies; see, e. g., [1, 2] for recent reviews. At a sufficiently high density N_a, a sample of atoms that are excited by a short pumping pulse into an incoherent state on one of the upper energy levels emits, after a certain delay time t_d, a powerful coherent pulse of SR. The phenomenon is due to an effective mutual phasing of the atomic dipole oscillators over the time $t < t_d$. The duration of the SR pulse, t_p, and the delay time are much shorter than the times of incoherent spontaneous emission and collisional relaxation in a medium. This is the distinctive feature of collective spontaneous emission, i. e. SR which makes the phenomenon so *different from standard lasing.*

However, in most solid-state lasers, including semiconductor lasers, the incoherent relaxation of polarization is much faster than the rate of stimulated radiative transitions, and cooperative effects in the oscillators' dynamics are suppressed. That is why the semiconductor lasers still do not exhibit experimentally the SR generation regime. In this report we point out that under certain conditions (basically, high photon losses from a cavity and very high pumping rate) SR becomes possible in quantum-well (QW) heterostructures, where the energy density of states is increased as compared with bulk semiconductors. We calculate the parameters of ultrashort coherent pulses obtained under *continuous pumping*, and demonstrate that the use of recombination SR can simplify essentially the technique of femtosecond pulse generation in semiconductors. Finally, the feasibility of obtaining superradiant generation from Ge/GeSi QWs is investigated.

2 Analysis of Maxwell–Bloch equations for semiconductor optics

The resonant interaction of most active media (including semiconductors) with coherent radiation is adequately described by Maxwell–Bloch equations [1-4]. In the semiclassical and mean-field approximations, and for slowly varying complex amplitudes of the field,

$\mathbf{E}(t)$, and polarization, $\mathbf{P_k}$, they take the following form:

$$d\mathbf{E}/dt + \mathbf{E}/T_E = (2\pi i\omega\Gamma/\mu^2)\sum_{\mathbf{k}}\mathbf{P_k}, \tag{1}$$

$$d\mathbf{P_k}/dt + (1/T_2 + i(\omega_\mathbf{k} - \omega))\,\mathbf{P_k} = -id^2\Delta N_\mathbf{k}\mathbf{E}/2\hbar, \tag{2}$$

$$d\Delta N_\mathbf{k}/dt + (\Delta N_\mathbf{k} - \Delta N_\mathbf{k}^p)/T_1 = \mathrm{Im}(\mathbf{E}^*\mathbf{P_k})/\hbar. \tag{3}$$

Here ω and μ are the eigenfrequency and the refraction index of a given axial mode of a cavity. We will assume for simplicity that only the fundamental transverse mode is self-consistently excited, with $\mu \simeq 3.5$ and the optical confinement factor $\Gamma < 1$. The field decay time T_E in an open cavity of length L takes a simple form in the case of purely radiative losses: $T_E \simeq 4\mu L/|c\log(R_1R_2)|$, where $R_{1,2}$ are the reflection factors at the cavity facets, c is the velocity of light in vacuum.

Taking into account only direct radiative transitions, we introduce an inversion, $\Delta N_\mathbf{k}(t)$, and an amplitude of polarization, $\mathbf{P_k}(t)$, of a given "$\mathbf{k}$-oscillator", that is, an electron and hole that have dipole moment d, quasimomentum $\mathbf{k}$, energies $\mathcal{E}_{e,h}$, and recombine emitting a photon of energy $\hbar\omega_\mathbf{k} = \mathcal{E}_e(\mathbf{k}) + \mathcal{E}_h(\mathbf{k})$. In Eq. (3) the term $\Delta N_\mathbf{k}^p$ is an inversion density supported by pumping (in the absence of generation). The time T_1 determines the incoherent relaxation rate of inversion. The time T_2 characterizes the incoherent relaxation of polarization for a given $\mathbf{k}$-oscillator (an electron-hole pair). Its value is typically very small, $T_2 \sim 0.1$ ps at room temperature, and is determined by the intraband scattering processes.

The criterion of SR (or superfluorescence) is usually formulated in terms of a linear initial-value problem, i. e., as a requirement that the growth rate of small initial perturbations of field and polarization in the *initially inverted* medium should exceed the incoherent relaxation rates [1, 2]: $\omega'' > 1/T_1, 1/T_2, \Delta\omega$, where the latter quantity is an effective inhomogeneous broadening determined by a band filling of particle states. It can be shown [2, 5] that in *bulk* semiconductors the requirements $\omega'' > 1/T_2$ and $\omega'' > \Delta\omega$ are usually incompatible, and incoherent relaxation should suppress or greatly reduce cooperative effects in stimulated recombination.

To increase the rate of stimulated recombination needed for SR, one can change the density of particle states by reducing an effective dimension of an electron-hole plasma in a semiconductor sample. Previous proposals included, e. g., excitonic SR [6] and SR in a quantizing magnetic field [2, 5]. Both schemes are not very practical since they require low temperatures or strong magnetic fields exceeding 0.3 MG. The SR regime in QWs discussed in this report seems to be achievable at room temperatures and under injection pumping.

We have analyzed numerically and analytically [7] the dispersion properties and dynamics of hot cavity modes and found that the conditions necessary for SR are satisfied in heterostructures consisting of 7–10 QWs with active layer thicknesses $L_z \lesssim 50$ Å and confinement factor $\Gamma \gtrsim 0.1$. For definiteness, the numerical estimates here and below are given for GaAs/AlGaAs QWs. The calculations were also made for other popular materials, with similar results.

3 Collective recombination and generation of femtosecond SR pulses

In order to obtain pulsed SR generation under a continuous pumping one must search for the range of parameters in which the regime of stationary laser generation becomes *unstable*. Analysis of the phase space of Maxwell-Bloch equations (1)–(3) shows [7] that instability occurs when $3/T_2 \lesssim \bar{\omega}''$, $(1/T_1 + 1/T_2) \lesssim 1/T_E \lesssim \bar{\omega}''$ and the pumping rate exceeds some threshold value specified below for given structure parameters. Here the reference value of the growth rate is $\bar{\omega} \simeq 2\times 10^{13}$ s^{-1}. Note an unusually high value of the required photon losses which implies a very low-Q (short) cavity. Indeed, it is the decay of the field that makes the steady state unstable against the stabilizing action of the polarization decay. An example of one-mode quasiperiodic SR generation in this range is presented in Fig. 1. We have also taken into account a slow "switching on" of a pumping by including a factor $(2/\pi)\arctan(\tau/50)$ into the pumping term $\Delta N_{\mathbf{k}}^p$ in Eq. (3).

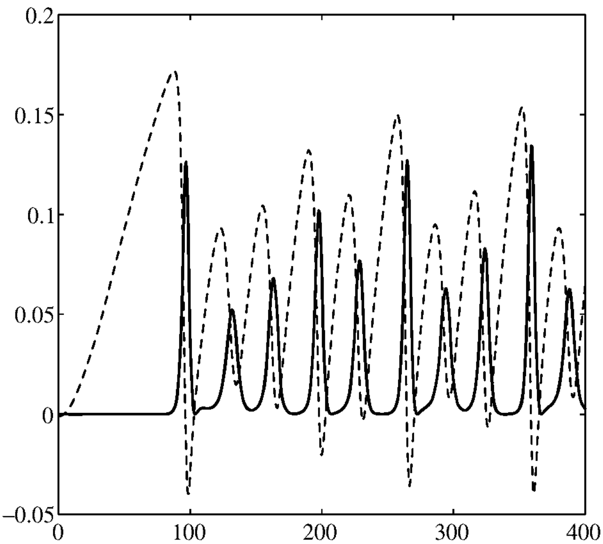

Fig 1. The normalized radiation density e^2 (solid line) and inversion n summed over the particle states in the spectral bandwidth $0.7\bar{\omega}''$ (dashed line) as functions of dimensionless time $\tau = \sqrt{2}\bar{\omega}''t$ in the regime of SR pulse generation under continuous pumping. Normalized relaxation times are $\tau_1 = 30$, $\tau_2 = 5$, $\tau_E = 2.5$.

For a structure of cavity length $L = 30\,\mu$m and confinement factor $\Gamma = 0.1$, consisting of N QWs with active layer thickness $L_z = 50$ Å, the coherent pulses shown in Fig. 1 have duration $t_p \simeq 50$ fs, the period between pulses $T \simeq 1-2$ s, peak power $\gtrsim 1$, and peak output intensity per pulse $I = \mu^2|E|^2L/(8\pi T_E) \simeq 100N$ MW/cm^2. Note that to provide a short enough decay time T_E, the reflection factors and the cavity length should be small, $R_1R_2 \sim 0.1$ and $L \sim 30-100\,\mu$m.

The pumping may be either continuous or pulsed. To provide high enough injection rate of carriers, the pumping current density should be very large, $J \gtrsim 3\times 10^3 N$ A/cm^2. Therefore, to prevent an excessive heating at room temperature, the pumping by short enough (submicrosecond) current pulses is desirable.

Another potential field of application for SR is a generation of coherent light pulses in the indirect band-gap semiconductors. Consider for definiteness Ge/GeSi QWs. It seems that the most promising way to reach the high level of stimulated radiative recombination in Ge active layers is to employ *direct* radiative transitions between the Γ-valley in the conduction band and the top of the valence band ($\Gamma_2' - \Gamma_{25}'$ transition). An absolute energy minimum of the conduction band, located in the L_1-point, is lower than the Γ_2'-minimum. Therefore, usually, the nonequilibrium carriers injected to the Γ-valley migrate very quickly to the L-minimum, with only a small fraction of them recombining radiatively. However, suppose that we are able to inject carriers to the direct minimum with the rate sufficient for the onset of collective SR recombination. In this case, since SR recombination has femtosecond timescale and proceeds faster than the intraband scattering of carriers to the L-minimum, nearly all carriers should contribute to the emission of femtosecond SR pulses. This may provide the unique way to obtain coherent optical emission from stimulated radiative recombination of carriers in Ge/Si structures.

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References

[1] Zheleznyakov V. V., Kocharovsky V. V. and Kocharovsky Vl. V. *Usp. Fiz. Nauk* **159** 193-260 (1989) (*Sov. Phys. Usp.* **32** 835-890 (1989)).
[2] Belyanin A. A., Kocharovsky V. V. and Kocharovsky Vl. V. *Quantum & Semiclass. Optics* **9** 1-44 (1997).
[3] Haug H. and Koch S. W. *Quantum Theory of the Optical and Electronic Properties of Semiconductors*, Singapore: World Scientific, 1994.
[4] Chow W. W., Koch S. W. and Sargent III M. *Semiconductor Laser Physics*, Berlin: Springer-Verlag, 1994.
[5] Belyanin A. A., Kocharovsky V. V. and Kocharovsky Vl. V. *Laser Physics* **2** 952-964 (1992).
[6] Misawa K., Jao H. and Kobayashi T. *J. of Lumin.* **48&49** 269-272 (1991).
[7] Belyanin A. A., Kocharovsky V. V. and Kocharovsky Vl. V. *Quant. & Semiclass. Optics* in press (1998); *Izvestiya RAN, Ser. Fiz.* **62** 372-383 (1998).